# Determination of Above Ground Carbon in Canada's Forests – A Multi-Source Approach

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ABSTRACT -Canada is a signatory to the Kyoto Protocol and must report on reforestation, afforestation and deforestation activities since 1990. Reporting commitments also include a baseline estimate of forest carbon stocks in 1990 and the monitoring of changes in carbon stocks leading up to the reporting period 2008 to 2012.

Canada has 10% of the world's forests (418 million hectares), which account for a significant amount of stored carbon. The determination of above-ground carbon stocks in the forest can be based on several sources: remote sensing, models of vegetation growth, book-keeping carbon models, and traditional forest inventories. Estimating above-ground carbon with remote sensing requires the fusion and integration of remote sensing data with topographic, forest cover and other geospatial information. Multi-temporal LANDSAT TM imagery was used in conjunction with GIS data to compute above-ground biomass from which the carbon content is determined. In addition to biomass, other key factors, which play a role in the determination of carbon stocks, include species and age distribution, forest structure, and climate variables. The paper reports on remote sensing experiments to determine the above-ground carbon stocks for a test site near Hinton, AB. It is expected that this approach will be useful in supporting Canada's reporting commitments on the sustainability its forest resources.

## INTRODUCTION

The Kyoto Protocol requires that the industrialized nations report on the state of their forests, including information related to carbon stored in forests, reforestation, afforestation, and deforestation. Canada has signed, but not ratified, the Kyoto Protocol. A new project has begun to monitor the forests of Canada using remote sensing. This project is called Earth Observation for Sustainable Development of Forests (EOSD) [1]. In addition to indicators of sustainable development, EOSD will report on above-ground carbon distribution across Canada.

Canada has 10% of the world's forests or 418 million hectares. This represents a very significant storage of carbon. An estimated 15 gigatonnes of carbon are stored in Canada's forest trees, and 71 gigatonnes in forest soils (not including over 110 gigatonnes in peat deposits [2], [3]). Remote sensing can be used to measure the above-ground carbon. Several countries have announced that they will use remote sensing to monitor the compliance of other nations with international agreements, such as the Kyoto and Montreal Protocols. The base year for the Kyoto Protocol reporting is 1990. The US Landsat satellites provide the longest temporal series of land remote sensing imagery.

In 1999 we began a project to demonstrate the measurement of above-ground carbon using a multi-source approach. This project was supported by the Climate Change Action Fund and the Canadian Space Agency. A 2612 $km^2$ test site near Hinton, Alberta was selected (Figure 1). Landsat imagery was acquired for six dates from 1985 to 1996. The Alberta Forest Service made available topographic data for the entire test site. The Alberta government also provided maps showing the spatial distribution of forest cover as mapped during the Phase 3 provincial inventory. The Canadian National Forest Inventory (CanFI) provided digital summaries of forest attributes on a 10 km by 10 km cell grid.

A carbon budget model of the Canadian Forest Sector (CBM-CFS) [4] has been developed which can be used to provide estimates of each of the components of the carbon distribution in the forests. CBM-CFS presently does not use remote sensing inputs. It draws on historical forest inventories (regional ecozones or CanFI), other geographic information, and meteorological data to compute the carbon distribution. A long-term goal of this research is to compare the carbon estimates from CBM-CFS with those from remote sensing. Subsequently, CBM-CFS could be modified to accept remote sensing inputs. These inputs could include forest classification and forest biomass at much finer spatial distributions than presently used. CBM-CFS requires three forest classes: conifers, deciduous, and mixed wood. CBM had been previously tested in the forest management area in Hinton managed by Weldwood [5]. Weldwood has detailed permanent sample plots, but the data collected by the company were not made available to us for this remote sensing study.

The forest species mix (lodgepole pine, white spruce dominant) in the Hinton test site is similar to that found for a site in British Columbia in the East Kootenays. Crestbrook Forest Industries previously provided detailed timber cruise and permanent sample plot data to us so that a relationship

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could be developed linking a remote sensing vegetation index with timber volume for mature coniferous forests. This relationship was used in this study [6].

## DATA FUSION

The test site covers approximately 27.5 townships. The Province of Alberta provided 16 1:20,000 digital NAD'83 topographic files. These files were merged to create a seamless digital elevation model for the test site with 25 m pixels. The range in elevations was 1331 m. Hydrology and road networks were included in the GIS files. The 1985 image was orthorectified using 17 ground control points (GCPs) and the DEM. The horizontal root-mean-square error (rms) was 0.39 pixels or 9.75 m. The 1990 and 1996 images were provided by RSI and geocorrected. A correction for topographic relief was applied with a 64-point sin(x)/x resampling kernel. Image-to-image registration to the 1985 base was then performed with a 16 by 16 sin(x)/x function resampling kernel. The Alberta Base vectors and 25 GCPs were used to assess the resulting accuracies of the geometric correction. The results were a rms error of 11.4 m for the 1990 image, and a 12.3 m rms error for the 1996 image. Data fusion for the three dates was better than 0.5 pixels. Table 1 lists the Landsat scenes and the dates of acquisition.

Table 1. Landsat 5 Acquisitions.

| Date | Path and Row |
|---|---|
| July 31, 1985 | P 45 R 23 |
| July 29, 1990 | P 45 R 23 |
| July 23, 1996 | P 45 R 23 |

Since there was no field work conducted at the site during these historical Landsat acquisitions, no corrections were made for atmospheric effects. The radiometry of each scene was compared to the 1985 scene. Regression relationships were developed between 1990 and 1985 and the radiometry of the 1990 image was linearly transformed to the 1985 base. Table 2 lists the regression equations for each Landsat band. (TM 1990')=a*(TM 1990) + b. There was no significant difference between the 1985 and 1996 radiometry.

Table 2. 1990 TM Radiometric Conversion to match 1985.

| Landsat TM Band | Slope (a) | Intercept (b) |
|---|---|---|
| 1 | 0.72 | 10.72 |
| 2 | 0.76 | 3.60 |
| 3 | 0.83 | 0.91 |
| 4 | 1.02 | -3.35 |
| 5 | 0.83 | 1.98 |
| 7 | 0.77 | 0.79 |

## ESTIMATING CARBON

The following steps were performed to create an estimate of above-ground carbon for each image: 1) fuse imagery with GIS files to common digital elevation base; 2) divide images into 1024 by 1024 tiles; 3) segment each tile into homogeneous objects using six TM channels and a 3 by 3 variance filter for edge detection; 4) create bit maps for clouds, cloud shadows, and water; 5) identify training segments for each class using GIS and forest inventory maps; 6) classify the segments; 7) classification accuracy assessment; 8) construct forest classes (softwood, hardwood, mixed wood); 9) cluster each forest class (softwood, hardwood, mixed wood) and retain most frequently occurring clusters (noise removal); 10) classify the segments in each tile with revised training classes; 11) mosaic the resulting classifications for the test site; 12) assess the accuracy of the classifications; 13) compute normalized difference ND45 for forest pixels; 14) apply 11 by 11 filter to ND45 images and compute biomass; 15) convert biomass to carbon; and 16) sum up carbon for each 10 km by 10 km cell for comparison with carbon from the National Forest Inventory (CanFI).

### Masks

The first mask on the imagery indicates the boundaries of the test site. Image analysis was restricted to be within the test site. A "no change" mask was created to identify forest areas that did not change from 1985 to 1996. Areas of no change were identified by comparing the ND45 images between the three dates and creating a range image. The histogram of the range image was thresholded to define the areas of no change (smallest range differences). Clouds and shadows were present in the 1990 and 1996 imagery. Masks were created to delineate the clouds and shadows so that these areas would not be included in the carbon estimation for 1990 and 1996.

### Forest Inventory

The National Forest Inventory (CanFI) consists of forest attributes tabulated on a 10 km by 10 km cell. The forest inventory summary statistics are provided by the provinces and territories based on their detailed forest inventories. As a result, the CanFI attributes span a data collection period of up to 30 years. The CanFI attributes are stored in Oracle relational tables. The attributes pertaining to the Hinton test site were extracted and placed in Access tables. The attributes extracted from the CanFI database included: cell identifier, stock, maturity, type, area, biomass area, biomass tonnes, and volumes.

### Segmentation

Tiles of 1024 by 1024 pixels were segmented into homogeneous objects. A 3 by 3 pixel variance measure was used to create a gradient image for each TM channel. An edge at any wavelength was included in the final edge image that was used to determine the segmentation of the TM image ([7], [8]). Segments were then selected as training segments based on Alberta Forest Service Phase 3 Inventory Maps. Mixed pixels at the edges of the segments were removed in a clustering process for the forest classes.

### Classification

The classes selected for the final classification are shown in Table 3. The conifer class contains at least 80% conifer and no more than 20% deciduous. The deciduous class is the opposite. All other forest groupings are called mixed wood.

Table 3. Selected Classes

| Number | Class Code | Description |
|---|---|---|
| 1 | 1 | Conifer |
| 2 | 5 | Mixed wood |
| 3 | 10 | Grassland |
| 4 | 13 | Barren rock |
| 5 | 16 | Cleared land |
| 6 | 18 | Scrub coniferous |
| 7 | 19 | Scrub deciduous |
| 8 | 20 | Treed muskeg |
| 9 | 21 | Clear cut |
| 10 | 22 | Clear cut – partial regen. |
| 11 | 23 | Clear cut – recovered |
| 12 | 26 | Mine / quarry |
| 13 | 30 | Water (blue) |
| 14 | 31 | Water (dark) |
| 15 | 32 | Cloud |
| 16 | 33 | Cloud shadow |
| 17 | 34 | Deciduous |

The segments were classified by Euclidean distance from the adjusted training segments. Classification accuracies were assessed against test and training data. The classification of the forest allowed us to create masks for forest, softwood, deciduous, and mixed wood. These are the classes required for the CBM-CFS.

### Biomass

Our initial plan was to use the permanent sample plot (PSP) data from Weldwood to develop biomass relations as a function of remote sensing vegetation indices, forest class, site index, and age class. These PSP data, however were not made available for this study. We, therefore, used a relationship developed in an earlier study for similar forest species ([6]). This relationship ($r^2$ = 0.953) for mature softwoods estimates the timber volume in $m^3$/ha as:

Volume in $m^3ha^{-1}$ = - 478.58 + 4.5041*ND45,
where ND45 is the vegetation index, averaged over an 11 by 11 pixel window, and defined by:
ND45 = 128*((TM4-TM5)/(TM4+TM5))+128.
This gives the timber volume associated with each pixel. In [9] the density values used for the dominant species in this test site were: spruce (360 kg/$m^3$), and lodgepole pine (409 kg/$m^3$). We chose a conversion factor of 409 kg/$m^3$ and converted pixel size to hectares to compute the biomass in metric tonnes. Computed ND45 values less than zero were set to zero.

### Above-Ground Carbon

The biomass in tonnes was converted to carbon in tonnes by multiplying by the conversion factor of 0.5 tonnes of carbon per tonne of wood [2].

## Results

The overall classification accuracies for each date were determined based on the weighted average of the individual classification accuracies. Weighting was determined by the frequencies of occurrence of each class. The results for the six-channel segment classifications were: a) 1985 - 81.5% correct; b) 1990 - 90.3%; c) 1996 - 85.4%. These accuracies compare favorably with the best obtainable for traditional forest inventories. Figure 2 shows the classified image for the test site for 1985. Figures 3a, and 3b show the resulting carbon images for the 1985 and 1996, respectively.

In a report on biomass derived from CanFI data ([10]), the following data can be obtained. The average biomass (t/ha) by forest type for Alberta is: Softwood – 82 t/ha, Mixed wood - 92, Hardwood - 68, Average 78. The average biomass (t/ha) by maturity class for Alberta is: Regeneration – 2 t/ha, Immature - 51, Mature - 105, Over-mature - 114, Average 78. By site class (productivity), the biomass figures are: Site 1 – 57 t/ha, Site 2 – 84, Site 3 – 114, Average 78.

Following the methods described previously, we determined the total above-ground carbon for the Hinton test site for 1985, 1990, and 1996. The results are shown in Table 4. The CanFI entries were based on the Phase 2 Inventory of the Alberta Forest Service (1980) and the biomass calculations by [10]. The carbon figures are in good agreement, with a remote sensing above-ground carbon average estimate of 5.50 +/- 0.30 megatonnes. However, the remote sensing forest classification resulted in a forest area 1.88 times larger than CanFI forest area. The Alberta forest inventory concentrates on the commercial forest sites. The remote sensing analysis includes all forests. The biomass estimates from the remote sensing data were 50% lower than those of CanFI. This may be an area dilution effect. Kurz and Apps [2] report an average carbon biomass of 46.5 t C/ha for a larger portion of Alberta which includes the Hinton test site. With 24 full townships available for comparison, we examined the correlations between remote sensing and CanFI.

Table 4. Comparison of carbon derived from CanFI with carbon obtained from remote sensing. The comparison area of the 24 full tiles is 240,000 ha.

| | CanFI | 1985 TM | 1990 TM | 1996 TM | Average TM |
|---|---|---|---|---|---|
| Forest Area (ha) | 85906 | 169446 | 167933 | 148052 | 161810 |
| Tonnes / ha | 67.5 | 33.3 | 33.8 | 34.5 | 33.8 |
| Carbon (Mt) | 5.87 | 5.66 | 5.70 | 5.15 | 5.50 |

For the areal estimates, we found:
(CanFI Area in ha) = 0.8024*(TM Average Forest Area) - 1830.7 with a $r^2$ = 0.3454.

For the biomass estimates we found no correlation between CanFI and remote sensing. If we accepted the average biomass figure of 67.5 t/ha from CanFI for Alberta forests, and the average forest area from remote sensing (161810 ha), then there would be 10.9 megatonnes of carbon in the Hinton test site.

Table 4 shows a decrease in above-ground carbon from 1980 (CanFI, 5.87 Mt) to 1996 (TM, 5.15 Mt). To determine the consistency of the carbon estimates from remote sensing, we applied the mask indicating those forest areas in the images which had not changed. The results are shown in Table 5. The no-change carbon estimates are: 1985 – 4.04 +/- 0.07 Mt; 1990 – 4.15 +/- 0.06 Mt; 1996 – 3.91 +/- 0.07 Mt. The average no-change carbon estimate is 4.03 +/- 0.12 Mt. These results show that the remote sensing procedure for classification and biomass estimation gave consistent results within 3%. Kurz and Apps [2] found with CBM-CFS simulations very little change in the biomass (<2%) over the period from 1985 to 1994, in good agreement with the remote sensing results.

Table 5. Remote sensing carbon estimates for forested areas which did not change.

| | 1985 TM | 1990 TM | 1996 TM | Average TM | Standard Deviation |
|---|---|---|---|---|---|
| Forest Area (ha) | 115830 | 118410 | 115036 | 116425 | 1764 |
| T/ha | 34.3 | 34.7 | 35.1 | 34.7 | 0.4 |
| Carbon (Mt) | 4.04 | 4.15 | 3.91 | 4.03 | 0.12 |

## Conclusions

Three Landsat 5 Thematic Mapper scenes were used to estimate above-ground carbon for a test site near Hinton, Alberta. The remote sensing carbon estimates were compared with the Canadian National Forest Inventory (CanFI) results. CanFI stores forest attributes on a 10 km by 10 km grid. Remote sensing estimates were averaged over the same grid and compared with CanFI. The average above-ground estimate for carbon from remote sensing was 5.50 Mt, while the estimate from CanFI was 5.87 Mt. Carbon estimates for forested areas which did not change over the 11 years were found to be the same within 3%. Remote sensing provided forest area estimates 1.88 times larger than CanFI. Remote sensing biomass estimates were 50% lower than CanFI, because remote sensing captures all of the existing treed areas and CanFI emphasizes commercial forests.

In the future, we will develop separate biomass relationships based on site index or age. ND45 saturates at different amounts depending upon the forest type and age class. Ground plots with accurate mensurational measurements are required to separate out these different biomass relationships with vegetation indices. A site on Vancouver Island has been selected to test this methodology of carbon estimation. For this new site, we have access to detailed permanent sample plot data. Landsat 7 with its panchromatic band may also permit a more precise determination of the segment boundaries, increasing the classification accuracies above the 81% achieved for this experiment.

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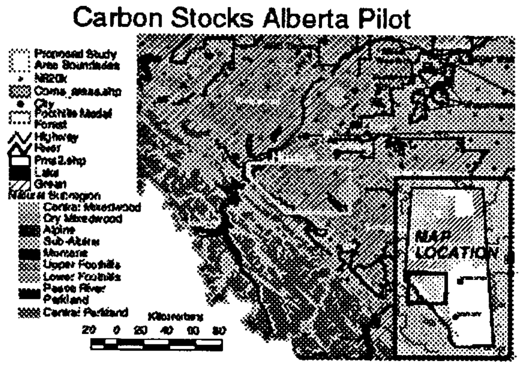


**Figure 1: Hinton, Alberta study site.**

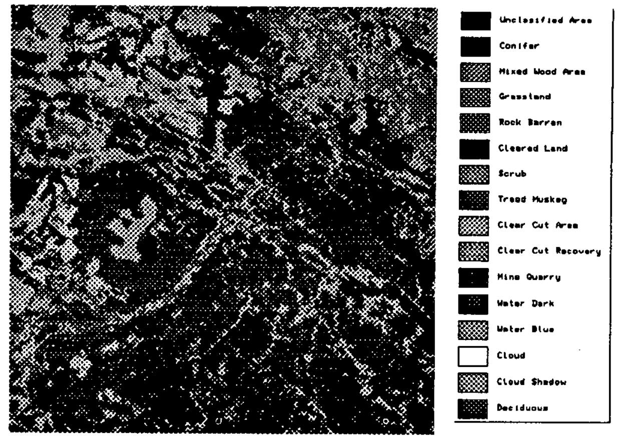


**Figure 2: Hardwood, softwood and mixed wood classification (1985 TM data)**

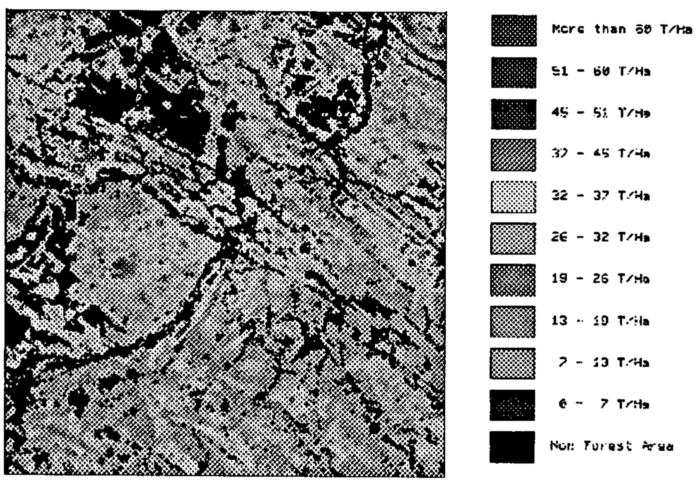


**Figure 3a: Computed carbon for 1985 TM data.**

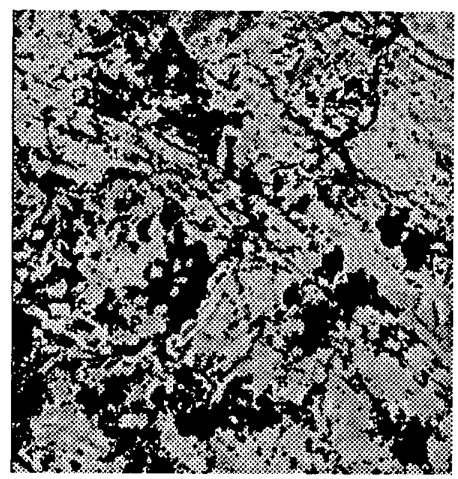

**Figure 3b: Computed carbon for 1996 TM data.**